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HIGH–IMPEDANCE ARTIFICIAL DELAY LINES

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High-Impedance

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INCREASING use is being made of distributed-constant electromagnetic delay lines as circuit elements in present-day electronic equipment. The characteristic impedance of these lines has been limited to values between 400 and 3,000 ohms.[1,2] Applications exist for lines with higher characteristic impedance. A brief discussion of the factors that determine the delay time and characteristic impedance will first be given, then ways of increasing the characteristic impedance will be discussed in detail.

The delay time, phase velocity, and characteristic impedance of a distributed-constant delay line can be derived from the simplified equivalent circuit of Fig. 1 where all losses have been neglected. These are

$$t_d = \sqrt{LC} \tag{1}$$

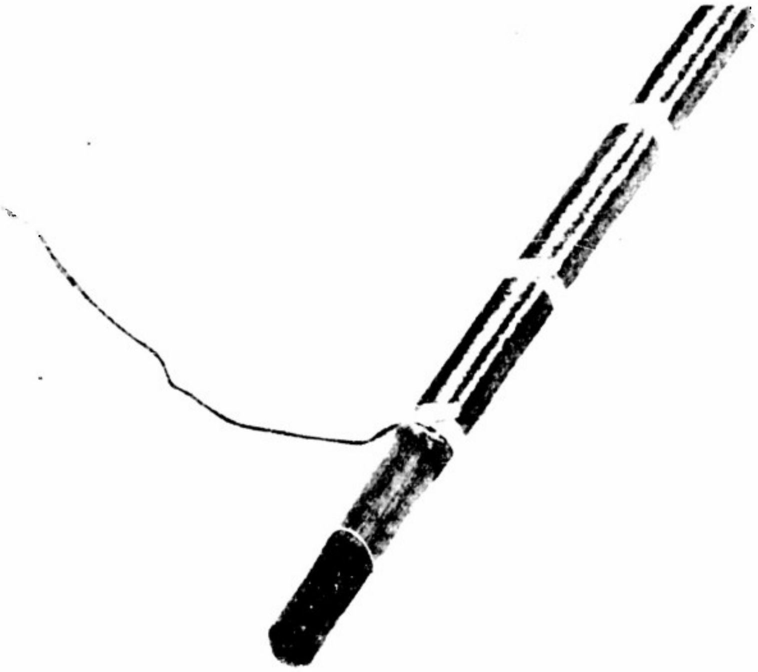
$$\beta = \omega \sqrt{LC} \tag{2}$$

$$Z_o = \sqrt{\frac{L}{C}} \tag{3}$$

where L = inductance per unit length and C = capacitance per unit length. If R and G, the resistance and conductance per unit length, are present but $R << \omega L$ and $G << \omega C$ the following more general equations apply[3]

$$T_d = \sqrt{LC}\left[1 + \frac{1}{2}\left(\frac{R}{2\omega L} - \frac{G}{2\omega C}\right)^2\right] \tag{4}$$

$$\beta = \omega\sqrt{LC}\left[1 + \frac{1}{2}\left(\frac{R}{2\omega L} - \frac{G}{2\omega C}\right)^2\right] \tag{5}$$



Enlarged view of end of wound delay line shows core details, dielectric and winding

$$Z_o = \sqrt{\frac{L}{C}}\left[1 + \frac{1}{2}\left(\frac{R^2}{4\omega^2 L^2} - \frac{RG}{2\omega^2 LC} - \frac{3G^2}{4\omega^2 C^2}\right) + j\left(\frac{G}{2\omega C} - \frac{R}{2\omega L}\right)\right] \tag{6}$$

It has been found that the attenuation of delay lines increases very rapidly with frequency above several megacycles.[4] The largest part of this increase was attributed to insulation loss. Experimental evidence in the form of lines wound with low-loss hand-coated wires substantiates this fact. At high frequencies R is proportional to $\sqrt{f}$. From reference 4 it is estimated that G is proportional to f^2 for Formex insulated wire.

It has been observed that the inductance of a delay line decreases at higher frequencies.[5,6,7] This is caused by phase shift per turn increasing so that although the turns are still magnetically linked as the frequency increases they add less and less to each other's magnetic field. A plot[7] of normalized inductance L/L_o and time delay T/T_o vs

$$\frac{d\,T_o}{l}\sqrt{f}$$

appears in Fig. 2 where d = diameter of line, T_o = time delay for low frequencies, l = length of line and f = frequency.

The effect of turn-to-turn capacitance has been studied.[6,8] At low

* This article is based on a paper presented at the 1952 National Electronics Conference. The conference paper will appear in the *N.E.C. Proceedings*.

Artificial Delay Lines

Distributed-constant delay lines for short pulses may be designed with characteristic impedances as high as 10,000 ohms. Typical line is 10 in. long, 0.2 in. in diameter, weighs less than 10 grams and provides delay of 3.7 microseconds

frequencies the effect of this capacitance is negligible as the phase of the voltage in each turn of the coil is the same. As the frequency increases the phase of the voltage in each turn changes. Thus the effect of the turn-to-turn capacitance increases with frequency until the phase shift per turn equals 360 degrees. This turn-to-turn capacitance has the effect of increasing C to the value

$$C = \frac{C_e}{1 - \left(\frac{\omega}{\omega_e}\right)^2} \qquad (7)$$

where ω is the angular frequency of the input signal

$$\omega_e^2 = \frac{1}{L'C'} \qquad (7')$$

where $L' = L/N$ = effective inductance per turn, C' is the self capacitance between two adjacent complete turns and C_e is the capacitance per unit length from winding to core at low frequencies.

The inductance thus decreases with frequency and the capacitance increases with frequency. If the magnitude of these two effects were the same, delay time would be constant with respect to frequency. If $\frac{2\lambda}{d} > 13$ (λ = wavelength) a fair equalization of delay time could be obtained.[9] This would require

$$\frac{C'}{C} = \frac{25 d^2 N}{4 (2\pi)^2} \qquad (8)$$

but C' =

$$\frac{\pi d K_e}{3.6 \log_e \left\{ \frac{x + s}{x} + \sqrt{\left(\frac{x + s}{x}\right)^2 - 1} \right\}} \qquad (9)$$

$$\doteq \frac{\pi d K_e}{3.6 \sqrt{2} \sqrt{\frac{s}{x}}} \ \mu\mu\text{f per turn}^{9}$$

where K_e = dielectric constant of wire insulation, x = diameter of wire, S = wire separation and d = diameter of coils.

Substituting $N = 1/x$ (for a close wound coil) and Eq. 9 in Eq. 8 we obtain

$$K_e^2 x^3 = \frac{S C^2 d^3}{15} \qquad (10)$$

where C is in micromicrofarads per axial centimeter.

The equalization of delay time by this procedure is done at the expense of decreasing characteristic impedance.

Another method of equalization of the delay time, likewise at the expense of characteristic impedance, is the use of patches.[4,9] Patches are bridging capacitors over a number of turns, effectively increasing C as the frequency increases. Lumped-constant phase correcting networks have also been studied.[10]

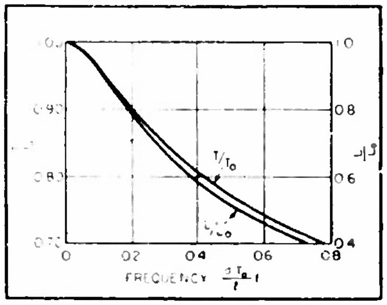


FIG. 2—Curves show effect on line inductance and delay

Equations 1 through 6 are derived on the assumption that the parameters R, L, G and C remain constant. Above a certain frequency we now see that R is proportional to $\sqrt{f}$, G is proportional to f^2, L decreases with increasing frequency and C increases with increasing frequency.

The resistance effect may be minimized by using small wire sizes

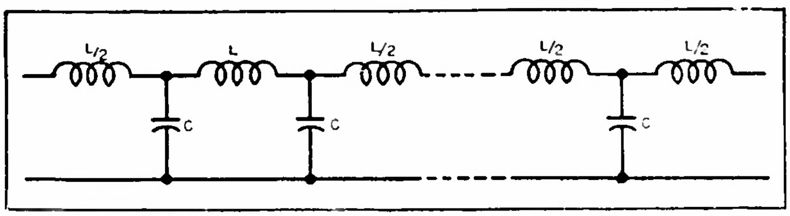


FIG. 1—Simplified equivalent circuit of a distributed-constant delay line of helix parameters

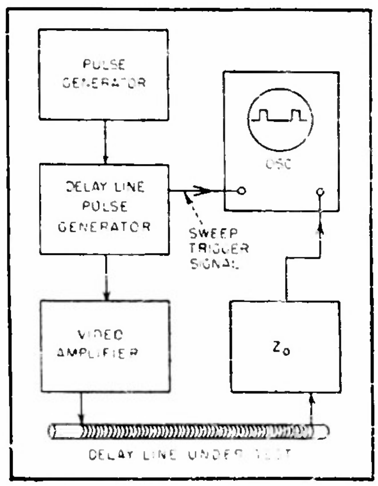


FIG. 3—Simplified block diagram of setup for testing distributed-constant lines

such as B & S gauge numbers 41, 44, 46 and 48. Little can be done about the conductance except to use low-loss insulation. Teflon-insulated magnet wire is now available which should have much lower insulation loss. The effects on both L and C may be reduced appreciably by winding the lines on a small diameter form such that the phase difference per turn is reduced. As shown by Eq. 3 one could increase the characteristic impedance by increasing L or decreasing C. If C were decreased, the time delay would decrease.

High-Z Lines

The purpose of the investigation, reported in this paper, was to produce lines having relatively large delays and high characteristic impedances. To achieve these goals both L and C were increased, but L was increased by a considerably larger factor than C.

To obtain as large a delay as possible it was decided to use the complete core as a ground. The capacitance per unit length can be varied by controlling the thickness and dielectric constant of the insulation material placed between the core and the winding. This large capacitance per unit length would necessitate a correspondingly large inductance per unit length to secure a high characteristic impedance.

The secret of success for the high characteristic impedance line is the method of obtaining the high inductance. First, a small wire size was chosen. As B & S gauge No. 48 copper magnet wire had a large attenuation and was too easily broken most of the work was done with No. 46 wire. With this wire a bank winding with approximately 3 layers was found necessary to obtain the necessary inductance.

The theoretical discussion of the compensation of a multilayer line will not be taken up at this time. The problem is quite complex with self capacitance from one turn to several neighboring turns and has not been completely solved. The discussion of the variation of time delay with frequency in the previous section is directly applicable only to single layer lines. A comparison of the calculations for single layer lines with the experimental results of multilayer lines appears later in this paper.

Line Construction

The lines were wound on $\frac{3}{16}$-inch diameter polystyrene cores 12 inches long. These cores were given several coats of silver conducting paint to form the ground strip. After an overnight drying period, the cores were axially slotted forming 36 thin strips, each strip being about 0.015 inch wide between 0.003-inch slots. A one-inch length of the core was left unslotted to facilitate the connection of the external ground lead.

The core was covered with a layer of insulating material to serve the dual purpose of insulating and controlling the winding-to-core capacitance. A 0.85 × 11.5 inch piece of Teflon tape 0.003 inch thick was wound around the core. This made 1.4 turns around the core. A number of small pieces of cellophane tape held the Teflon on the core until the line was wound. The tape was removed piece by piece as the line was wound.

The winding was done on a lathe. To provide uniform wire tension, both to secure a good winding and to prevent breakage, the wire feeding device shown in the photograph was used. The wire tension is adjustable over a range of about 10 to 70 grams and is continuously indicated by a pointer.

A wire guide attached to the longitudinal feed of the lathe was placed about $\frac{1}{16}$ inch from the core, which was chucked in the lathe. The longitudinal travel of the wire guide was 0.00066 inch per turn. As this distance is a fraction of the wire diameter, the result was a multiple layer coil approximately bank wound. The far end of the core was attached to a counter chucked in the tailstock. A steel drill rod was inserted through a hole in the core for rigidity. A 10-inch long winding was wound on the core. Lines have been wound with speeds varying from about 200 to 500 rpm.

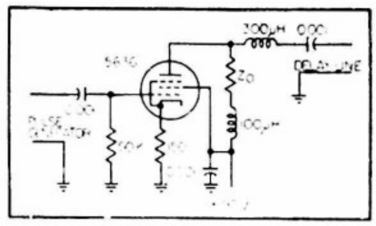


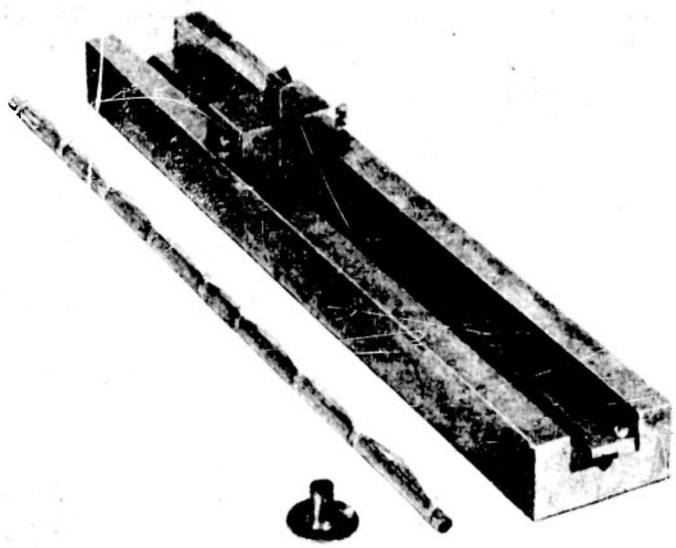
FIG. 4—Video amplifier circuit diagram

A piece of No. 26 wire was soldered to the ends of the winding and secured to the winding with polystyrene dope.

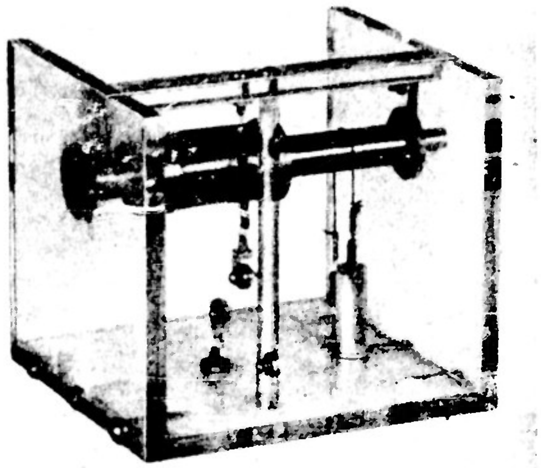
The method for determining the characteristic impedance of these delay lines is based upon the fact that no reflections occur in an ideal-

Table I—Summary of High-Impedance Distributed-Constant Delay Line Characteristics

	L (mh)	C ($\mu\mu f$)	Z_0 (ohms)		t_d (μsec)		rise times (μsec)			attenuation (db/μsec delay)	winding length (inches)
			meas (real part)	calc	meas	calc	t_{r0}	t_r	t_{rt}		
No. 41 line....	21.0	518	5,600	6,600	3.5	3.6	0.1	0.11	0.1	0.3	10
No. 46 line....	22.1	652	5,600	5,830	3.75	3.8	0.1	0.15	0.12	0.4	10
No. 48 line....	21.70	161	5,600	6,800	3.1	3.2	0.1	0.18	0.15	1.3	10
High Impedance.	40.7	150	9,000	9,500	1.5	4.3	0.08	0.2	0.18	0.4	9.3
No. 44 line....	40.7	150	10,000	9,500	1.5	4.3	0.08	0.21	0.22	0.2	9.3



Slotting device for preparing delay line cores. Indexing head is shown in foreground



Constant tension wire feeder permits use of wire as small as No. 48 in delay lines

ized delay line terminated in its characteristic impedance. The characteristic impedance of a line whose parameters are a function of frequency would most certainly be a function of frequency. The value of the characteristic impedance in a practical case involving complex waves must therefore be compromised for minimum reflections over the band of frequencies for which the line is designed to operate.

Measurements

In making measurements, the lines are terminated at the input as well as the output to minimize any possible secondary reflections at the input. A suitable means of determining the effective characteristic impedance when the line is used to delay rectangular pulses is to feed the pulse itself into the delay line and to adjust the terminating impedances for minimum reflections.

A block diagram illustrating the experimental method for determining the characteristic impedance of these delay lines and for recording the response of the delay lines to rectangular pulses appears in Fig. 3.

The oscilloscope sweep is triggered by the input pulse. A camera, mounted on the oscilloscope, records the input and output wave shapes of the delay line. The load impedance of the video amplifier was made equal to the characteristic impedance of the line. A diagram of the video amplifier appears in Fig. 4.

The pulse distortion and attenuation were also measured with the equipment connected as shown in Fig. 3, using the oscilloscope camera. The delay time as well as the rise and fall time was likewise measured on the oscilloscope. The delay time was defined as the time between the midpoint of the leading edge of the input and output wave forms. The rise and fall times were defined as the time duration between the 10 and 90-percent values of the pulse amplitude. The pulse duration was defined as the time between the 10-percent values. The attenuation was measured by comparing the amplitudes of the input and output pulses.

Results

The data on a particular line, typical of those wound follows:

Core diameter is 0.188 inch, with 36 slots.

Dielectric is Teflon 0.003 × 0.85 × 11.5 inches.

Length of winding is 10 inches with 1,520 turns per inch (0.00066 inch per turn) of No. 46 HF wire 0.0019 inch in diameter.

The electrical characteristics of the line measured at 1,000 cps were, R = 3,660 ohms, L = 22.1 mh, G = 0 and C = 652.1 μμf.

Impedance and time delay calculated from these measurements, are Z_o = 5,830 ohms and t_d =3.8 microseconds. The experimental data obtained on this line were Z_o = 5,600 ohms resistance in series with a parallel network of a hundred-microhenry choke and a 2,200-ohm resistance (determined for minimum reflection with 0.3-microsecond pulse).

Time delay was 3.75 microseconds and t_{ri} = rise time of 1-μsec input pulse = 0.1 microsecond; t_r = rise time of 1-μsec output pulse = 0.14 microsecond as

$$t_r = \sqrt{t_{ri}^2 + t_{rl}^2} \qquad (11)$$

where t_{rl} = rise time output pulse if a perfect input pulse were applied to the line. Thus t_{rl} = 0.1 μ sec.

Photographs of the input and output waveforms appear in Fig. 5 for pulse durations of 0.30, 0.37, 0.62 and 1.0. Input and output waveforms superimposed to a larger scale are also included. The reflections appearing between the input and output pulses no doubt occur at points where the spill over from true bank winding was particu-

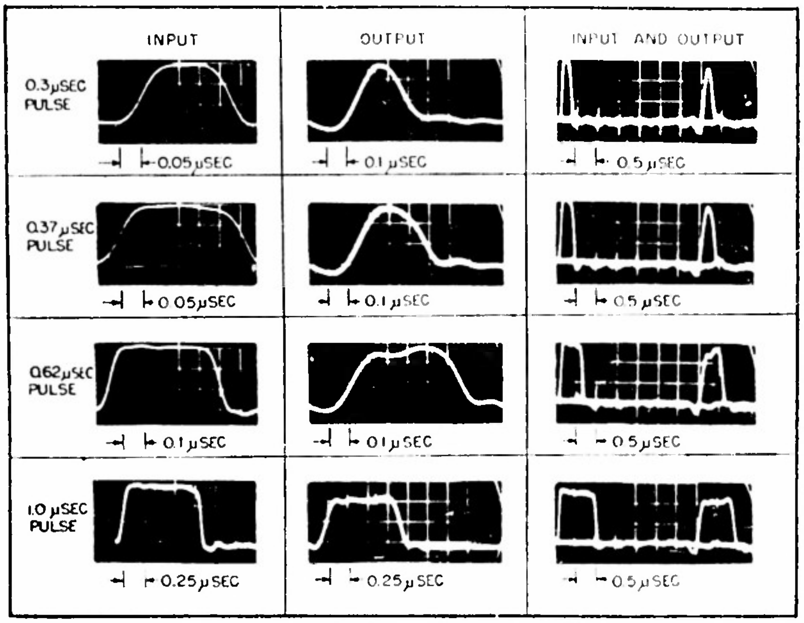


FIG. 5—Pulse response of 5,600-ohm line wound with No. 46 wire

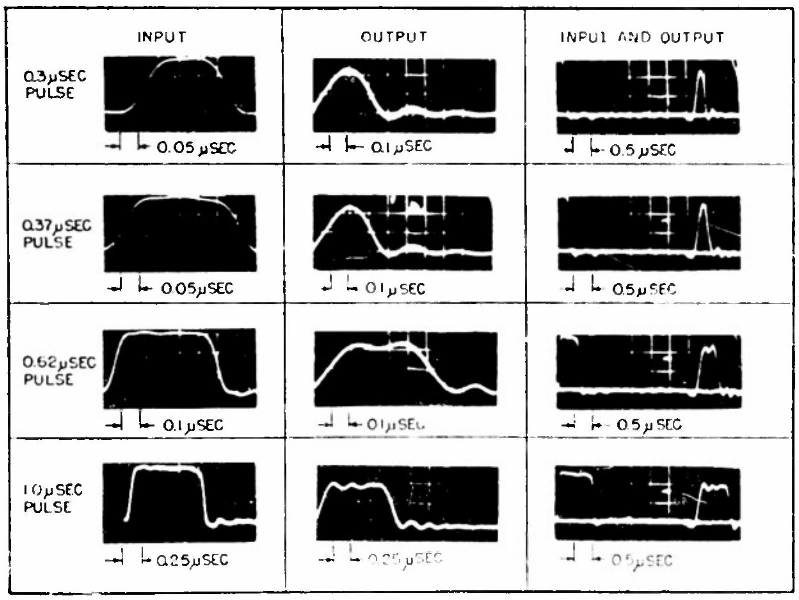


FIG. 6—Pulse response of 5,600-ohm line wound with No. 44 wire

larly bad. All photographs were taken with the same value of terminating impedance which was the value obtained as the best impedance match with a 0.3-μsec pulse applied. In the case of the longer pulse durations, slightly better waveforms can be secured by reterminating the line. An example will be shown later.

Substituting in Eq. 10, on the supposition that this equation holds for a bank winding, we find the winding-to-core capacitance should be 0.29 μμf per centimeter for proper equalization. This value was obtained using 3.6 for the dielectric constant of Formex and 0.0002 inch as the thickness of the dielectric. From the measurements, the capacitance to core was 25.7 μμf per centimeter. The effect of the stray capacitance is therefore much higher for the multilayer line. Equations are being derived which give very good agreement.

The value of ω_o may be calculated from Eq. 7. If $L' = 1.46$ μh and $C' = 2.2$ μμf from Eq. 9, $\omega_o = 0.56 \times 10^9$. The resonant frequency thus is 89 mc.

Resonant Frequencies

Resonant frequencies of 124, 165, 215, 235, 332 and 375 mc were obtained experimentally. The 235-mc reading had a considerably higher Q than the others and was probably the resonant frequency of a single turn. The 124-mc frequency had a very low Q. No readings were observed from 60 to 124 mc.

The thickness of the dielectric used in calculating the resonant frequency was determined by measuring the overall diameter of the insulated wire with 1/10,000-inch micrometers. The wire was coated with X-Var which chemically attacks the Formex. After the wire was wiped clean the diameter was measured again. This method does not give extreme accuracy.

The resonant frequency of the inductance of one turn and the core capacitance of that turn is calculated to be 368 mc. This value checks the 375-mc value very closely. If one assumes that we have a fictitious single layer winding and each turn has an inductance 3 times that of the former single turn ($L' = 4.38$ μh). We have effectively lumped up the inductance of three layers into one.

If the equivalent single-layer winding outlined above is assumed, the resonant frequency of the inductance of one turn and the capacitance to core of one turn is 212 mc. This checks the 215 megacycle value very closely.

No explanation is apparent for the 124 and the 332 megacycle readings. The fact that there were two layers of insulation over 40 percent of the core and one layer over 60 percent of the core might account for some of these resonances.

Waveforms

Photographs of the waveforms of a line of similar dimensions except 1.5 layers of Teflon and wire size changed to No. 44 with 55 grams tension appear in Fig. 6. The winding was approximately 4 layers. The termination was the same except the series inductance was raised to 250 μh. A comparison of Fig. 5 and 6 shows the delay and attenuation to be slightly less for the No. 44 line although the phase distortion and small reflections along the line are slightly greater. This is probably due to the spill over being greater with the four layer winding.

A line was wound using 1.8 layers (1.1 inch wide strip) of Teflon and wire size changed to No. 48 with 20 grams weight tension with an average of 2.2 layers on this winding. The terminating impedance used was the same as in the previous case except the series inductance was changed to 200 μh. The line was terminated for minimum reflection using a 0.3-μsec pulse input. The waveforms of this line appear in Fig. 7. It will be noted that the attenuation has increased appreciably. There is more ringing on the top of this wave. The line was reterminated with a 1-μsec pulse applied. The terminating impedance turned out to be a 5,600-ohm resistor.

Lines with higher characteristic impedances than 5,600 ohms have been obtained using a ¼-inch diameter core and 2¾ layers of Teflon tape. The characteristic impedance, when terminated with a 0.3-μsec pulse applied, was increased to 9,000 ohms in series with a 400-μh choke. The input impedance (shunt impedance in output of video amplifier) was 7,400 ohms in series with an inductance of 400 μh. Photographs of the waveforms of this line appear in Fig. 8.

This particular line had only 14,165 turns and the winding was 9.3 inches long. It had a time delay of 4.5 μsec, or a time delay of almost 0.5 μsec per inch. When the line was reterminated using a 1-μsec pulse, the terminating impedance turned out to be a 10,200-ohm resistor. The output impedance of the video amplifier was increased to 11,000 ohms. The waveforms of this termination also appear in Fig. 8. This line was wound with No. 44 wire.

The characteristics of these lines are compared in Table 1. The real part of the terminating impedance (the best value for 0.3-μsec pulses) is listed in all cases. In the case of the high characteristic impedance line, the characteristics for the best one-microsecond pulse termination also appear. The attenuations listed were measured values with a one-microsecond pulse applied to the line. From Fig. 5 and 6 it will be noted that the attenuation is greater for shorter pulse durations.

From the data presented, delay lines with impedances of 5,600 ohms and reasonable attenuations for pulse widths less than 1-μsec can be obtained. It appears likely that lower attenuations can be obtained if better winding techniques can be developed for the No. 44 gauge wire. The availability of Teflon-insulated magnet wire in small wire sizes should aid in the reduction of attenuation and improvement of phase response.

The authors are indebted to J. F. Peoples for his assistance and to M. F. Davis for his encouragement.

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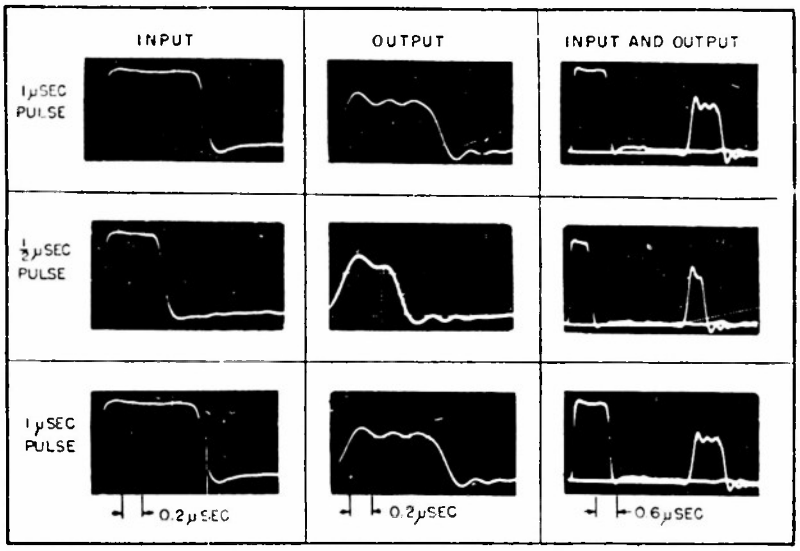

FIG. 7—Oscillograms show 5,600-ohm line wound with No. 48 wire terminated for a 0.3 μsec pulse (top and middle) and 1.0-μsec pulse (bottom)

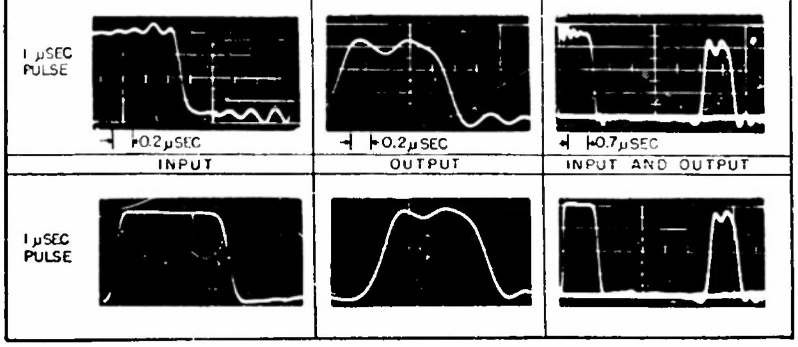

FIG. 8—Oscillograms show effect of different terminating impedances on 9,000-ohm line wound with No. 44 wire. Top is terminated for 0.3 μsec pulse. Bottom is terminated with 10,000-ohm resistor